A SYSTEM APPROACH TO PLASTIC HOUSE DESIGN
Case Study: Green Bay, Taiwan

by

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Submitted to the Department of Architecture on May 8, 1985 in Partial fulfillment of the requirements for the Degree of Master of Science in Architecture Studies.

Abstract

Since the building industry is getting more and more sophisticated in today's world, many new technologies lead us to many new possibilities for producing houses which we never would have thought of producing in the past. New technology for a designer implies the use of new rules. As a designer wants to use a new technology in a meaningful way, information which is useful to an engineer might not be directly useful to an architect. To say it clearly, two things are important for a designer to do before he starts a design:

1. He must understand not only the technology itself, but also the implications of it for design form.

2. He must organize the technical information in a way which he can use to evaluate the design.

Thus, following this format, my reason for choosing plastic houses the object of this study is because there are many new implications and much new design information of the plastic technology for us to understand; For example, plastic houses may be transported to areas that are difficult to reach by any other means of transportation than helicopters. This may lead to a very interesting approach toward the relationship between technology and architectural design.

Thesis Supervisor: Eric Dluhosch
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And last, to my father and mother, for their love and solid support during my studies abroad.
## CHAPTER 7. BUILDING SYSTEM DESIGN

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### CONCLUSION

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1.1 Background of the Development of the Plastic House

The first real plastics structure was lonel Schein's house in Germany (Fig. 1), shown at the Paris Exhibition of 1956 but designed and constructed in 1955. The concept of the house was based upon the growth of a snail's shell, so that the house consists of a basic circular living space with cooking area, sanitary block and warm-air heater, to which a number of bedroom units may be attached at will. As the shell grows to accommodate the snail, so this house grows to accommodate the family. The planning was advanced for its time, e.g., the successful reconsideration of the elements of clip-on heating, moulded sculptural doors, and above all a most revolutionary bathroom core were the features which made the house a truly worthy foundation for the evolution of plastics in architecture. (Ref. 14, pp. 44)

The Monsanto House of the Future (Fig. 2) in the U.S.A was designed by Hamilton and Goody, and built in 1957, two years after the lonel Schein's house. This is still
probably the best known plastic structure in the world. It was without doubt, brilliantly engineered. GRP (glass fiber reinforced plastic) shells with multiple honeycomb cores cantilevered from a concrete core with windows in the flank of each arm -- a demonstration of how plastics can overcome some of the most difficult stress conditions. Two years after the Monsanto house, the first British shell structure (Fig. 3) was designed by a group working in the architects' research and development section of the British Railways (Eastern Region). Three shells were designed which could be put together in a variety of ways to meet different functions, these were constructed of an inner and outer skin of 0.3cm GRP and a 2cm core of expanded phenolic, all on a female GRP mould. The first structure was assembled at Thameshaven Junction in Essex in 1961 and over three hundred were subsequently produced including variations on the design. This is probably the most successful GRP structure yet to go into production since Ionel Schein's house. (Ref. 14, pp. 50)
1.2 Recent Trends

Basically, two areas are suggested for the potential use of plastics in housing module design:

1. Portable Housing Modules for the oil and mineral exploration industry: (Fig. 4)

The expanding industrial development of Southeast Asia, particularly in the areas of oil and mineral exploration, has created a substantial need for portable housing modules for use as personnel living quarters in remote exploration areas, construction site offices and accommodations on offshore production, etc.

Until recently these needs have been met by units of conventional wood frame and plywood panel construction, mounted on steel skids. In 1974, Sail Craft Ltd., an American-owned and managed fiberglass fabrication firm in Singapore, designed a fiberglass portable module which, it was felt, would resolve many of the shortcomings associated with wooden construction. The use of fiber glass/foam sandwich panels would eliminate the maintenance problems due to the rotting of the structural members and attack by
termites. A high degree of rigidity and strength was achieved by the use of polyurethane foam as the core material. The fiberglass unit would also be extremely light, thereby lending itself particularly well to helicopter lift operations. Finally, the use of fiberglass would permit considerable flexibility in structural and industrial design and would provide an attractive and modern finished appearance. (Ref. 22, pp. 3-7)

2. Second home:

Between the market segment for campers and complete houses for second homes, there exists a market for plastic houses. One example is the O'Dome. (Fig. 5)

O'Domes are manufactured and marketed by Tensile Structures, Inc. of Plymouth, Michigan. After pilot production and test marketing, the company began full-scale operations in 1971. While promotion has been directed at the second home market, many other practical uses of O'Domes were or can be considered. These include primary homes for exhibit buildings, recreational buildings, food service facilities, and medical clinics. (Ref. 3, pp. 1-3)

After this brief review of the history and recent trends of plastic houses, several important reasons of consideration for plastic as a major building material can be offered as follows:

1. Formability:

Because the material has no inherent shape, it must be formed into its final configurations. This makes possible
the use of efficient structural shapes that use a minimum of material for maximum structural efficiency.

2. Strength, lightness, toughness:

   Because of their toughness and strength, reinforced plastics can be used in thin sections, leading to lightness with a consequent reduction in dead load.

3. Corrosion resistance:

   Environments that corrode metal or rot wood, frequently have no effect upon reinforced plastics. (Ref. 19, pp. 10-12)
1.3 Study Objective

The objective of this thesis is to explore the implications of a new technology (the manufacturing technology for plastic houses) for a specific building system type (matrix house shell for living) and to find an optimal design process for designing this kind of house by incorporating the new technology productively and correctly. To achieve the objectives listed above, the emphasis of this thesis is on the following three aspects:

1. The implications on the form of the house design by using plastic as a building material.

2. The framework which can be used to organize the technical information on plastics and to evaluate building system design.

3. A building system design of a plastic house for Green Bay, Taiwan, is used to test the framework.

By using this approach, a prototype industrialized house design can be generated in a rational and systematic way.
1.4 Approach Method

The System Approach has been used as the study method. Basically, seven questions will be addressed in the different stages of the study and the research steps will be built around these questions. These seven questions respond the six chapters of my thesis, and the research steps follow the subdivision for each chapter.

Question 1: What is the study objective? This question has already been answered on the previous pages.

Question 2: What are the implications in building system design, based on the physical properties of this material?

Step 2.1: Identify the ingredients of the material (i.e., plastic).
Step 2.2: Identify the physical properties of plastics.

Question 3: How to classify the system from the architectural point of view?

Step 3.1: Identify the classification criteria for hyperbolic paraboloid curves.
Step 3.2: Identify the classification criteria for domes.

For the purpose of this thesis, the System Approach is defined as "a process which is used in viewing a problem as a set of interrelated parts which work together for the overall objectives of the whole". (Ref. 5, pp. 57)
Step 3.3: Identify the classification criteria for synclastic shapes.

Step 3.4: Identify the classification criteria for pneumatic structure.

Step 3.5: Identify the classification criteria for tube shapes.

Step 3.6: Identify the classification criteria for rigid frame structures.

Question 4: How to classify the existing technologies used to produce existing systems?

Step 4.1: Identify the classification criteria for production methods.

Step 4.2: Identify the classification criteria for erection and transportation methods.

Step 4.3: Identify the classification criteria for bathroom units.

Step 4.4: Identify the classification criteria for jointing methods.

Step 4.5: Identify the classification criteria for reinforcement methods.

Question 5: What is the context of Green Bay for building system design?

Step 5.1: Identify the natural environment of Green Bay.

Step 5.2: Identify the technical level of the design context.

Step 5.3: Identify the planning objectives of the developer.

Question 6: How to find the most appropriate system for GREEN BAY?
Step 6-1: Evaluate the structural shape alternatives.

Step 6-2: Evaluate the production method alternatives.

Step 6-3: Evaluate the erection and transportation alternatives.

Question 7: What is the physical design based on the evaluation?
CHAPTER 2. INVESTIGATION OF BUILDING MATERIALS FOR THE PLASTIC HOUSE

2.1 Identify the Ingredients of Building Material for the Plastic House

2.1.1 GRP (Glass Fiber Reinforced Plastic)

GRP can be classified as one of the most important materials in the fiber/matrix composite groups. The basic idea of the composite is to use the plastic flow (plastic resin) to transfer the load to the fiber; this results in a high strength, high modulus composite. The aim of the combination is to produce a two-phase material in which the primary phase, which determines stiffness and is in the form of particles of high aspect ratio (fiber), is well dispersed and bonded by a weak secondary phase (matrix).

The desirable functional requirements of the fibers in a fiber reinforced composite are:

1. The fiber should have a high modulus of elasticity in order to give efficient reinforcement.
2. The fiber should have a high ultimate strength.

The matrix is required to fulfil the following functions:

1. To bind together the fibers and protect their surfaces from damage during handling and fabrication.
2. To transfer stress to the fibers efficiently by adhesion and/or friction. (Ref. 7, pp. 27-29)

Thus, the physical ingredients of GRP can be classified into the follows:

1. The plastic resin function as the matrix part:

Plastic consists essentially of two elements, carbon and hydrogen. The carbon possesses four valencies (Fig. 6) which has the ability to satisfy any of these valencies by combining with other carbon groups or other groups of atoms having an unsatisfied valency. Plastics are organic materials with very high molecular weights constructed from simpler repeating units under suitable conditions of temperature and catalytic action. The "building up" of plastics from simpler units is called polymerization and plastics are known as high polymers. (Fig. 7)

Although the number of individual plastics runs into many hundreds, they can be broadly classified into two groups: thermoplastic plastics and thermosetting plastics.

Thermoplastics consist of linear polymer molecules which are not interconnected. The chemical valency bond along the chain is extremely strong, but the forces of attraction between adjacent chains are weak. Because of their

![Fig. 6](image1)

![Fig. 7](image2)
unconnected chain structure, thermoplastics may be repeatedly softened and hardened by heating and cooling respectively.

Thermosetting plastics are in a liquid or plastic stage once, and then harden irreversibly; this chemical reaction is known as polyaddition, polymerization or curing, and on completion of this reaction the material cannot be softened or made plastic again without change of molecular structure. Because of their cross-linked molecular structure, they are more resistant to heat, chemicals and solvents than thermoplastics are. Among all of the thermosetting plastics resins, polyester and epoxy are the commonest materials used as the matrix part of GRP. (Ref. 7, pp 27-30)

2. The fiber glass function as the fiber part:

Glass fibers are manufactured for the reinforced plastics industry by the rapid drawing of melting glass from an electrically heated furnace continuously. According to its fabric shape, the glass fiber is classified into the following three groups:

a. Chopped strands are continuous strands chopped into 50 mm lengths. Due to the method of dispersing these fibers in the matrix, the distribution is generally very uneven and consequently the laminates are not usually manufactured with this form of reinforcement.

b. Chopped strand mats are manufactured from chopped strands and probably represent the most important form
of glass fiber reinforcement for building components. The glass strands are bonded together in a random, two dimensional manner with a resinous binder and the resulting laminate has exceptionally good interlaminar cohesion and impact strength.

c. Woven rovings are used in mouldings and laminates to produce high directional strength characteristics. Bidirectional roving cloth laminates have high strength properties in two directions at right angles to each other, which can be used in conjunction with chopped strand mats to give bulk and extra strength to laminates.

Of the two major components of glass reinforced plastics composites, glass fiber is considerably stiffer and stronger than the resin matrix. The mechanical and end use properties of a composite are therefore highly dependent upon the content and properties of the reinforcement and upon the arrangement of the fibers in the matrix.

(Ref. 7, pp. 30-34)
2.1.2 Foam Plastic

Rigid foams are two phase systems of a gas dispersed in a solid phase plastic; in most cases the solid plastics represent only a minor property and utility of the foam. They are produced by adding a blowing agent to chemical formulations and this causes the materials to expand and to increase their original volume many times by the formation of small cells. Like solid plastics, rigid plastics foams can be thermoplastics or thermosetting plastics materials, and they share the advantages and limitations of the solid phase; in addition, the density, cell geometry and gas phase composition can be varied to modify their products. Among all the foam plastics used in the construction industry, polyurethane foam is the most important one because of its excellent low thermal conductivity, good high temperature resistance, low vapour permeability and the property of insitu foaming. (Ref. 7, pp. 89-94)
2.2 Identify the Physical Properties of the Building Material

By using plastics as a building material, an understanding of some of their basic attributes is helpful in determining whether or not to employ plastics in a given application. Among the most important for buildings are strength, stiffness, thermal response, permeability, fire resistance, and durability. A detailed description is not given here, but the properties of most importance in building are briefly treated.

2.2.1 Mechanical Properties

There are two major requirements when designing structural components:

1. The deformation under load must be within the prescribed functional and aesthetic considerations.
2. Fracture or rupture should not take place within their scheduled life time.

To satisfy these requirements it is necessary to have information on two particular mechanical properties, namely stiffness and strength. Therefore, a discussion of the mechanical characteristics will largely revolve around these two properties.

The strength of plastics varies from a very high value for reinforced plastics to low for some soft, flexible plastics. Generally speaking, GRP and some unidirectional laminates are among the strongest of most of the commercial...
materials, especially on a strength-to-weight basis. Strength is not the same in tension, compression, and bending. Fig. 8 gives approximate ranges of tensile strength of plastics. Compression and bending strength usually run higher.

As to the stiffness factor of plastic, we can find in Fig. 9 that even the stiffest reinforced plastics and laminates lie well below other building materials except for wood. This factor presents a major problem for the use of plastics in construction.

There are two basic ways to overcome the stiffness problem.

1. Sandwich construction:

Sandwiches are composites in which layers of distinctly different materials are combined to give strength and stiffness with minimum weight and thickness combined with insulation, plus the necessary resistance to wear and tear. In sandwiches as employed in buildings, two relatively hard, stiff, strong, thin facings are bonded to a thick core of
relatively light, weaker, and usually less stiff material. The facings provide the resistance to bending, the core taking up the shear and stabilizing the thin facing against buckling, and the geometry of the combination providing high overall stiffness. Generally speaking, the use of this kind of structure implies a high production cost of the material. (Ref. 7, pp. 68-70)

2. Surface structure:

Surface structures such as domes, shells, and folded plate systems show convincingly that stiffness is primarily a function of the geometry of the structure and thus depend on the strength properties of the material of which they are made of. Thus, the required rigidity of the structure is then derived from its shape rather than from the material.

The structural shapes of plastic may be placed under one of the three following geometric forms:

a. Folding plates

b. Synclastic and anticlastic shells
c. Domes

Among these three categories, folding plates are generally used for large span structures or roof systems, only synclastic, anticlastic shells and domes contribute significantly toward small house module designs. (Ref. 7, pp. 75)

2.2.2 Thermal Conductivity

Compared with metals, plastics are heat insulators. Most
solid, unmodified plastics have a conductivity higher than wood but lower than that of glass, brick, or concrete. Conductivity of filled, laminated, and reinforced plastics depends upon the nature of the additive. (Fig. 10)

Among all of the plastics and other building materials, foam plastics are the best heat insulator available. Thermal conductivity of foams depends upon density. In general, the lower the density, the lower the thermal conductivity, but if the density becomes too low, the cell size increases to the point where appreciable convection currents may be set up in the cells, and conductivity rises. (Ref. 7, pp. 120)

2.2.3 Thermal Expansion and Contraction

The extent of thermal expansion and contraction of plastics is appreciably larger than that of many other building materials. (Fig. 11) Reinforced plastic has a thermal expansion coefficient close to wood but still higher than other building materials. Allowances in design must therefore be made for these dimensional changes, either by

---

**Fig. 10**

**Thermal Conductivity**

- Foamed plastic
- Wood
- Concrete
- Glass
- Brick

**Fig. 11**

**Thermal Expansion**

- GRP
- Wood
- Steel
- Aluminum
- Glass
- Concrete
accommodating them in the shape of the component by using curved or folded surface or by providing expansion joints. (Ref. 4, pp. 67-68)

2.2.4 Fire Resistance

Because plastic materials are organic in nature and are inherently combustible, they will decompose or burn when in contact with fire. Besides, some plastics may produce large volumes of carbon monoxide and smoke, and some of the least flammable plastics may give off the heaviest smoke. If constituents such as chlorine, fluorine, nitrogen are present in the plastic, they will also be present in the gases given off during fire.

To solve this problem, fillers such as calcium carbonate, china clay, and asbestos impart varying degrees of flame retardancy to plastics. Aside from this, greater fire penetration resistance can be achieved by the use of a cheap fire-resistant inner linings such as asbestos or plasterboard. Alternatively a sandwich laminate can be used with a fire resistant core material. (Ref. 4, pp. 72-74)

2.2.5 Durability

Durability for plastics is often difficult to assess due to lack of information, since it is a relatively new material and the aesthetic property of plastics, which is very important for the performance of durability, is hard to quantify.
In general, appearance of the exposed surfaces of a plastic component may change significantly due to weathering, and this in some cases may be sufficient to render the product aesthetically unacceptable. The most significant factor responsible for changes in appearance is sunlight, particularly its ultraviolet component. Other factors influencing degradation are temperature, humidity and the permeability of the exposed surface; the last controls the penetration of oxygen and the escape of the products of degradation.

Fillers and pigments have a major effect on the appearance and durability of plastics. The use of flame retardant additives may aggravate yellowing of the exposed surfaces of the plastic.

Besides, the mechanical properties of plastics may also decline on weathering, especially tensile strength and impact strength which are sensitive to surface deteriorations.

Two important factors upon which the durability and weathering performance of a plastic composites depend are:

1. The choice of resins for the gel coat and for the matrix of the composite i.e., an appropriate type of reinforcement must be used.

2. The provision of the required level of quality control to ensure a suitable production environment, correct fabrication procedures and adequate curing for the resin. (Ref. 4, pp. 74-75)
CHAPTER 3. CLASSIFICATION OF EXISTING SYSTEMS

In this chapter, several existing systems are investigated and classified into six categories (Saddle surfaces, synclastic curves, domes, pneumatic structures, tubes, rigid frames.), according to orthodox structural theory. These six categories will be used as the design alternatives for the system design in Chapter Seven. Each category will be carefully defined, according to its structural principles, to be followed by a design evaluation.

The classification criteria for the evaluation can be divided into two parts:

1. From the viewpoint of their exterior shapes:
   a. Whether the system is easy to expand vertically:
      The objective is to check the vertical section of the systems to see whether the units can be stacked easily to expand vertically.
   b. Whether the system is easy to expand horizontally:
      The objective is to check the boundary shape of the systems to see whether we can combine the units easily to expand horizontally.
   c. Whether the system is structurally sound:
      Basically, the six categories can be divided into two groups; a group which takes advantage of the structural shape (saddle surfaces, synclastic curves, domes, pneumatic structures) and a group which does not (tubes, rigid frames). The objective of this criterion is to identify these two
groups.

2. From the viewpoint of their interior shapes:

Having examined the systems from an exterior shape viewpoint, we will further evaluate the systems from the viewpoint of their interior shapes. The basic three criteria of such an evaluation are the following:

a. Whether the system is easy to combine with a regular rectangular cladding systems:

The objective is to check whether the system is easy to combine with the infill system of the cladding such as doors, windows and so on. For example, the boundary shape of rigid frame systems is normally close to being rectangular and thus is very easy to incorporate with standard doors and windows, whereas the boundary shape for a dome will be more difficult to combine with standard cladding elements. This situation will lead to an increase of the system's cost, since non-standardized products for the cladding will have to be used.

b. Whether the system is capable to accommodate regular partition systems easily:

The objective is to check whether it is easy to incorporate standardized two by four partition into the system. For most of the systems which have a curved vertical section, either a dropped ceiling or special elements have to be produced to solve this problem thus increasing the production cost of the system.
c. Whether the interior space is used efficiently:

This item can be examined from two different viewpoints:

(1). The objective is to check whether the system can accommodate regular furniture. For example, if a system has a curved horizontal or vertical section, special mold-in or built-in furniture around the perimeter of the house may be needed, and this will increase the production cost. Otherwise interior space may be wasted by the furniture arrangement, by avoiding curved interfaces.

(2). The objective is to check whether there is a vertical section of the system where the interior space is too low for use. For example, the vertical section of the exterior perimeter is always lower than that of the center part for the dome system. This problem can be solved by changing the integrity of the shape but this requires that extra reinforcement will be needed for the edge of the changed part.
3.1 Saddle Surfaces

1. Formation of the saddle surfaces: (Fig. 12)

The formation of the saddle surfaces can be described as a family of identical parabolas which are inverted and suspended between two other parabolas that arch upwards. The resulting surface is saddle-shaped. The saddle is curved in two mutually opposed directions. (Ref. 18, pp. 230)

2. Structural behaviour: (Fig. 13)

When a load is applied to the saddle surface, the buckling deflection causes the increase of the curvature of the downward parabolas. This deflection will be resisted by the upward parabolas. The tensile strength of the upward parabolas will resist the compressive strength of the downward parabolas to keep the shape stable when a load is applied. (Ref. 18, pp. 231-232)

3. Structural considerations: (Fig. 14)

The loading of a saddle surface is transferred by the arch system of the downward parabolas to the suspension system of the upward parabolas. Each edge has to resist the thrusting force of one axis and the tensile force of the other. In general, a rib system is applied along the downward direction of the parabolas to reinforce the system. (Ref. 18, pp. 232-233)

4. Case study: My-My system (Fig. 17,18)

This system is basically a sandwich construction with a fire retardant polyester resin skin and a urethane foam core. Along the downward direction of the parabolas, a folded
pattern is molded in the surface of the rear part of the system to reinforce the system against buckling.

The system is produced as a completed finished box with mold-in furniture along the perimeter of the system. Because of the difficulties related to the installation of partitions, the bathroom is built as a separate unit, attached to the main living unit. Thus, the complete system contains a living unit with service units located outside. (Ref. 10, pp. 23-25)
Evaluation (Exterior Shape):

Advantages:
1. Structurally sound because of the double curvature. (Fig. 16)

Disadvantages:
1. The basic unit is hard to expand horizontally because the plan is usually a hyperbolic shape. (Fig. 15)
2. The basic unit is hard to expand vertically because of its irregular vertical section. (Fig. 18)
Evaluation (Interior Shape):

Advantages:
1. There is no vertical section too low for human use.
   (Fig. 21)

Disadvantages:
1. The boundary shape has to be adjusted to accommodate standardized cladding systems. (Fig. 19)
2. It is hard to install interior partitions because of the complicated shape. Service spaces, such as toilets or
Kitchens are always conceived as separate units which connect with the living spaces. (Fig. 20)

3. Special built-in or mould-in furniture has to be used around the perimeter of the system to make the use of the interior space more efficient. (Fig. 21)
3.2 Domes

1. Formation of the domes: (Fig. 22)

The formation of the domes can be described as the rotation of a semi-circle (or a shape close to a semi-circle) around a vertical axis. The vertical section of a dome is called the meridian, the horizontal section is called the parallel, the parallel which has the biggest diameter is called the equator. (Ref. 18, pp. 213)

2. Structural behaviour: (Fig. 23)

We propose to use the hemisphere to illustrate the action of doubly curved shells. Imagine a narrow strip cut out of a hemisphere. In isolation this strip will tend to act like an arch. This narrow semicircular arch has a tendency to sag at the crown and bulge at the sides, the amount and direction of deflection depending on the deviation of the arch from the line of pressure. The same tendency to deform will be characteristic of any number of similar, adjacent, arch-like strips. When continuity is restored, however, the three-dimensional action of the shell begins to make itself felt. The elements on the upper zone of the hemisphere, which tend to sag inwards, thrust against each other to form a solid cap, in which all the forces are tied together horizontally and form an annular band, which restrains their individual tendencies to bulge. In this zone the meridional stresses are compressive and the horizontal stresses tensile. (Ref. 18, pp. 214-215)
3. Structural considerations: (Fig. 24)

The buckling resistance can be raised by adding ribs along the direction of the meridians and parallels. This method is seldom used since ribs will disturb the interior space.

A compression ring is usually used in the upper part along the parallels to increase the annular strength to resist the thrusting force. (Ref. 18, pp. 215)

4. Case study: O'Dome (Fig. 25, 26)

The basic prefabricated component of the O'Dome is a triangular panel of fiberglass skin and a cellular urethane core. In erection, 18 of these panels, plus 6 other major components, are assembled, interlocked, and cabled together, and then bolted down to form a super ellipsoid dome structure with a 7.5m diameter base and an interior height of 2.85m.

The basic panel contains a 0.8 kg density urethane foam core sandwiched by skins of fire retardent polyester bonded fiberglass. The base of the panel has a steel bar molded into it through which it is bolted to a wooden deck or a concrete slab.

The panels come out of production flat and are shipped that way to the building site. Onsite the panels are bent into their final curved shape, connected to an aluminum ring at the top, interlocked at their tongued and grooved edges, and further secured by a tensioned aircraft cable threaded through the panel cores.

The assembled O'Dome provides about 53 square meter of
unobstructed interior space. Six other components, in addition to the wall panels, provide for a doorway, sliding glass door, and a skylight with acrylic glazing.

(Ref. 12, pp. 45-47)
Evaluation (Exterior Shape):

Advantages:
1. The basic unit is structurally sound because of the double curve.

Disadvantages:
1. The basic unit is hard to expand horizontally. (Fig. 25, Fig. 27)
2. The basic unit is hard to expand vertically. (Fig. 26, 28)
Evaluation (Interior Shape):

Disadvantages:

1. It is hard to incorporate standardized cladding elements with the boundary shape. The problem can be solved by either disturbing the curved form or using special cladding elements. (Fig. 29)

2. It is hard to incorporate standardized two by four
partition elements into the system. (Fig. 30)

3. It is difficult to accommodate regular furniture along the system's perimeter. There are two solutions to this problem:
   a. The shape is adjusted to accommodate regular furnitures. (Fig. 31)
   b. Built-in or mold-in furniture can be used in the perimeter part of the system. (Fig. 31)

4. There is inefficient interior space near the perimeter part of the system too low to use. There are two solutions to this problem: (Fig. 32)
   a. The shape has to be adjusted to make the space usable.
   b. An elliptical shape in section is used to increase the ceiling height.
3.3 Synclastic Curves

1. Formation of the synclastic curves: (Fig. 33)

Synclastic curves belong to the category of the translational shell. The formation of the synclastic curve can be described as a downward curve (parabolas or semi-circles, or shapes close to these) along another downward curve perpendicular to it. (Ref. 18, pp. 220)

2. Structural behaviour: (Fig. 34)

The form of the synclastic shape can be regarded as a transformation of the cylindrical shape. The surface is curved twice, in both the longitudinal and transverse directions, the result is a shell of increased natural stiffness with the loading being transferred to the edge arch from the arch system along both axes. The structural behaviour of the center part of the shell is close to a shallow dome with compressive strength along its meridian and parallel directions. (Ref. 18, pp. 221)

3. Structural considerations: (Fig. 35)

The edge of this shape has to be reinforced to resist the thrusting force of the arch.

Compression rings can be used in the upper part of the curve to increase the annular strength of the shape. (Ref. 18, pp. 223)

4. Case study: Poly-Pod System (Fig. 38, 39)

Viewed from the top, the pod is triangular in shape with sides of equal length and rounded corners. Each pod sits on a central cylindrical base connected to the ground.
and through which the utilities enter.

Each of the triangular shapes of the pods may be assembled into a variety of room shapes and sizes; by varying the length of the support column they can be adapted to many surface typographies.

As more pods are added together, they become more stable and rigid. The smallest unit is composed of three pods with the columns in a tripod placement providing good lateral stability in any direction. The total dwelling unit can become like a living thing, adding elements and subtracting them as the demand dictates. (Ref. 21, pp. 5-9)
Evaluation (Exterior Shape):

Advantages:

1. The basic unit is easy to expand horizontally. (Fig. 36)
2. The basic unit is easy to expand vertically. (Fig. 37)
3. The basic unit is structurally sound because of the double curvature. (Fig. 39)
Evaluation (Interior Shape):

Advantages:

1. The boundary shape is very easy to adjust to accommodate standardised cladding elements. (Fig. 40)
2. Built-in furniture is not necessary. (Fig. 42)
3. There is no inefficient space in the vertical section where is too low to use, since the curvature of the vertical section can be controlled to a moderate degree. (Fig. 42)
Disadvantages:

1. The system is hard to combine with standard two by four partition elements. Either a dropped ceiling or special ceiling elements have to be used. (Fig. 41)
3.4 Pneumatic Structures

1. Formation of pneumatic structures: (Fig. 43)

Pneumatic structures are one of the most important shapes of the membrane structure group. A pneumatic structure is formed when a membrane has been filled with air in order to support exterior pressure. (Ref. 13, pp. 5)

2. Structural behaviour: (Fig. 44)

The loading of the structure is resisted by the interior air pressure and the membrane stress caused by this pressure has a positive relationship with the diameter of curvature of the structure. (Ref. 13, pp. 6)

3. Structural considerations: (Fig. 45)

A cable is generally used to change the structure into a form with smaller curvature to decrease the membrane stress. (Ref. 13, pp. 7)

4. Case study: Xanadu System (Fig. 48, 49)

The basis of construction of the Xanadu system is the spraying of polyurethane foam insulation on the inside of large hemispheric balloons. After the foam cures, the balloons are removed, leaving a shell of solid insulation. Doors and windows are then formed into place.

Xanadu took about six weeks to construct; plumbing and electrical wires are sprayed into place during construction. The dome has no super structure. The sphere shape is very strong and resistant to the elements. Ultraviolet rays from the sun which could damage the foam are blocked out with a sunscreen paint. The interior is protected with a fire-coating product. (Ref. 26, pp. 10-11)
The significance of this kind of structure on building system design is mainly a result of its production method. Thus, the comments for this part will be discussed in the production method part of chapter 4.
3.5 Tubes

1. Formation of the tubes: (Fig. 50)

The formation of the tubes can be described as the translation of a enclosed curve along a straight line perpendicular to it. (Ref. 18, pp. 225)

2. Structural behaviour: (Fig. 51)

The tube is a shape derived from the cylinder, the action of a cylindrical shell can be understood by imagining it replaced with a folded plate. In the direction of the span the flat elements between folds act like small beams, transferring the loads to points A and B. (Fig. 51) However since they are continuous at the folds, they are capable of resisting shear. Accordingly, they mutually restrain each other's tendency to deform and thus increase the carrying capacity of the structure as a whole. (Ref. 18, pp. 227)

3. Structural considerations: (Fig. 52)

The shape of the structure is preserved by means of transverse stiffeners at each end. The connection between these stiffeners and the shell must be capable of transmitting shear. (Ref. 18, pp. 228)

4. Case study: Filament Winding Housing System (Fig. 54)

The system shell is a monocoque sandwich structure. It has equal thickness GRP skins of 0.3 to 0.35cm and a polyurethane foam with a thickness of 15 to 23cm.

The materials for the endwalls consist of 2.54cm thick sandwich panels with reinforced plastic skins and a polyurethane foam core, 0.6cm plate glass, and aluminum
operating sash end exterior doors. These components are attached to the shell by using a structural neoprene zipper gasket, which is both mechanically fastened and bonded to the shell.

The reinforced vinyl-faced gypsum wallboard is selected as the interior partition material which is attached to the shell with a mechanically fastened butyl zipper gasket. Doors and frames are integral with the system. To keep the floor flat, a 1.6cm plywood floor system is supported on a light open steel frame.

The bathrooms are molded reinforced plastic units which are complete with wiring, heating, and internal plumbing. Piping for the housing unit is to be located in the floor assembly, and all internal connections are to be made in the on-site factory. Site connections are made through the bottom part of the shell. (Ref. 16, pp. 12-15)
Evaluation (Exterior Shape):

If the vertical section in the long axis is close to a rectangular shape:

Advantages:
1. The system is easy to expand horizontally. (Fig. 53)
2. The system is easy to expand vertically. (Fig. 54)

Disadvantages:
1. The system does not have the structural advantage of a double curved shape.
If the vertical section in the long axis is close to a circular shape:

Advantages:
1. The system is easy to expand horizontally along its long axis. (Fig. 55)

Disadvantages:
1. The system is hard to expand vertically. (Fig. 56)
2. The system does not have the structural advantage of a double curved shape.
Evaluation (Interior Shape):
If the vertical section in the long axis of the system is close to a rectangular shape:
Advantages:
1. The boundary shape can easily accommodate standardized cladding elements. (Fig. 58)
2. Built-in or mould-in furniture is not needed. (Fig. 61)
3. There is no inefficient interior space in the system. (Fig. 63)

Disadvantages:

1. The system does not accommodate easily standardized partition elements. Special ceiling and floor elements are needed. (Fig. 59)

If the vertical section of the system is close to a circle:

Disadvantages:

1. There is inefficient interior space in the vertical section where is too low to use. (Fig. 62)

2. It is hard to incorporate standardized cladding elements along the boundary shape. (Fig. 57)

3. It is hard to incorporate standardized partition elements in the system. Special ceiling and floor elements are needed.

4. Built-in or mold-in furniture is needed along the perimeter of the system. (Fig. 60)
3.6 Rigid Frames

1. Formation of the rigid frames: (Fig. 64)

The most simple frame system is a post and lintel structure system where the lintel is simply supported by the post. When rigid connections are used to connect the post and lintel, the total system is called a rigid frame system. (Ref. 18, pp. 139-141)

2. Structural behaviour: (Fig. 65)

When a vertical load is applied, the lintel sags and the rigid connection forces the post to move outward. This deflection is resisted by the horizontal thrusting force of the post base which forces the post bottom to move back to its original position. At this time, both the post and the lintel bend and a bending moment occurs. (Ref. 18, pp. 142-143)

3. Structural considerations: (Fig. 66)

Ties are usually used to connect the post bottoms to resist the thrusting force, which causes the post bottom to move outward.

4. Case study: Sprayed Plastics Housing Units (Fig. 67)

The monocoque construction was sprayed fabricated in a female mould using chopped fiber strands, polyester facings and a urethane foam core. The system is reinforced by a rib system along its longitudinal direction.

The interior was conventionally finished with 1.3cm plaster wallboard fastened to steel studs, which were foam encased to the inner sandwich surface. (Ref. 17, pp. 23)
Evaluation (Exterior Shape):

Advantages:
1. The basic unit is easy to expand horizontally. (Fig. 67)
2. The basic unit is easy to expand vertically. (Fig. 68)

Disadvantages:
1. Structurally, this is a very bad example of using plastic because it does not take advantage of the structural shape. Sandwich construction has to be used which increases the material's cost radically.
Advantages: (Interior Shape)

1. The system easily accommodates standardized boundary elements. (Fig. 71)

2. The system easily combines with standardized two by four partition elements. (Fig. 72)

3. There is no need for built-in or mould-in furniture. (Fig. 73)

4. There is no inefficient space in the vertical section of the system. (Fig. 74)
Other Possibilities:

This is a system usually used for large span structures.

A structure of this kind of system is a space grid made by other kinds of material, plastic is only used as the cladding.

The structure of this system is a wooden frame. Plastic is only used as cladding which does not resist major loads.

Note: Structurally, these are not reasonable solutions for plastic house design.
CHAPTER 4. CLASSIFICATION OF EXISTING TECHNOLOGIES

This chapter will classify existing technologies used to produce and erect plastic houses into five categories (production methods, erection and transportation methods, subsystems, joints, reinforcement). The discussion will include both critical problems of the technology and the implications or influences of these problems on building system design.
4.1 Production Methods

4.1.1 Hand Lay-Up Method

1. Production method:

   In this technique only one mould is used, and this may be either male or female, generally made of GRP. A suitable master pattern is prepared (Fig. 78), and from this GRP moulds may readily be made.

   To prevent bonding of the GRP components, a release agent is applied to the mould and then allowed to dry before any lay-up is undertaken. After this operation, a layer of resin rich area, called gel coat, is applied to the mould. This layer is used to protect the surface of the product and also determines the surface quality of the product.

   After the gel coat has become tacky but firm, a liberal coat of resin is brushed over it and the first layer of glass reinforcement is placed in position and consolidated with brush and roller. (Fig. 79) The glass fiber may be in the form of chopped strand mat or woven fabric, which is precut to the correct size. Subsequent layers of resin and reinforcement are then applied until the required thickness of the composite is reached. (Ref. 7, pp. 25-27)

2. Critical technical points:

   a. Curing shrinkage:

   A GRP may shrink by 0.1 to 0.4 percent during curing, and since there are two moulding processes between the pattern and the finished product, the net shrinkage may be
as much as 0.8 percent. The manufacturer gradually learns from experience how much to allow for shrinkage, depending on the shape of the unit, the resin, and the temperature change expected.

b. Demolding:

Although it is clearly desirable to design for simple moulds it is possible to develop "split moulds" with movable sections to achieve return angles for the convenience of demolding.

c. Mould width:

If the mould is too large or too complicated in shape, the fabricator cannot get to all the areas in order to lay-up an even coating of glass-fiber and resin, while at the same time ensuring good compaction and ease of rolling out. The ideal panel width is one where the operator can reach all parts of the mould easily, say 2m width. Length could theoretically be infinite, but is limited to 4 or 6 meter subject to handling on site and size for transportation. For more complex shapes, moulds may be tilted to allow the fabricator easier access. (Fig. 80)

d. Gel coat operation:

Great care and skill is needed in this operation to produce an even coating without trapping air bubbles or dirt. The thickness should be carefully controlled: if the gel-coat is too thin it will not give enough protection; but if the coating is too thick, crazing, cracking, as well as reduced impact resistance in use, is likely to occur.
e. Catalyst control:

Manufacturers must also control the quantity of the catalyst used: excessive catalyst will cause the mixture to overheat (the chemical reaction produced gives off heat) resulting in cracking and crazing; while inadequate catalyst will produce insufficient curing. Cutting catalyst levels, and low workshop temperatures will produce inferior laminates which perform badly. (Ref. 25, pp. 509-517)
**Tools and Equipment:**

1. Master pattern mold (usually made by wood). (Fig. 78)
2. Brush and roller. (Fig. 79)

**Implications:**

1. Labour intensive production method.
2. Slow production rate.

**Critical Technical Problems:**

1. Mould width (workability). (Fig. 80)
2. Gel coat operation (thickness control).
3. Curing shrinkage control.
4. Additives and catalyst control.
5. Ghost effects (appearance control).

**Advantages:**

1. Low capital investment.
2. Freedom of the product shape.

**Disadvantages:**

1. Quality control is based on skilled labour.
2. Slow production rate.
4.1.2. Spray-Up Method

1. Production method:

The spray-up technique is less labour intensive than the hand lay-up method. During the spray-up operation, glass fiber roving is fed continuously through a chopping unit, and the resulting chopped strands are projected onto the mould in conjunction with a resin jet. (Fig. 81) The glass fiber resin matrix is then consolidated with rollers. (Fig. 82) The technique requires considerable skill on the part of the operator to control the thickness of the composite and to maintain a consistent glass/resin ratio.
(Ref. 7, pp. 28-29)

2. Critical technical points:

   a. Thickness control:

   The technique requires greater skill than the hand lay-up method on the part of the operator to control the thickness of the composite and to maintain a consistent glass/resin ratio.

   b. Other considerations are the same as in the hand lay-up method. (Ref. 25, pp. 702-704)
Equipment and Tools:  
1. Spraying gun. (Fig. 81)  
2. Same as hand lay-up method.

Implications:  
1. Labour intensive production method.  
2. Slow production rate. (faster than hand lay-up)

Critical Technical Problems:  
1. Thickness control. (more critical than in hand lay-up method)  
2. The same as in hand lay-up method.

3. Experienced workers are needed.  
4. Limitation on the size of the components.

Advantages:  
1. Low capital investment.  
2. Freedom of product shape.

Disadvantages:  
1. Quality is more difficult to control than in hand lay-up method.  
2. Can not satisfy mass markets.  
3. Limitation on product size. (Fig. 83)
4.1.3 Filament Winding

1. Production method:

First, the steel mandrel is assembled in the field by joining together the vertical plates which are hinged at the corners and at the center of each of its four sides. (Fig. 84) Then, hoop wraps are applied around the mandrel by rotating the mandrel on a turntable supported by an air bearing and using a sending tower with an elevator carriage which advances the roving up and down the mandrel. (Fig. 85)

Second, preassembled core sections with longitudinally oriented glass-filament skins are applied to the mandrel against the inner hoop wrap. Following this, the final outer shell hoop wraps are wound around the core sections attached to the mandrel. (Fig. 86)

Third, the complete structure with the mandrel is moved to a curing area where the composite materials are cured with heat lamps located around the shell and inside the mandrel. (Fig. 87)

Finally, when curing is complete, the mandrel is removed from the filament-wound tube by using jackscrews to retract each side section of the mandrel. The mandrel is cleaned, expanded to its winding position, and returned to the winding table ready to start spinning the next unit. (Ref. 16, pp. 12)
2. Critical technical points:

a. Demolding:

In the production of typical large-scale filament wound structures, the mandrel is usually restrained by filament tension inside the finished shell and therefore must be destroyed to be removed. To solve this problem, a specially designed mandrel with flexible extending jackscrews has to be produced which increases the production costs.

b. Corner stiffness:

A structural analysis of the proposed shell system indicates a possible need for greater stiffness at the four corners of the tube to provide for transfer of high shear and bending stress at these points. This consideration complicates the construction process. The most serious difficulty is to provide for the winding of the inner skin. Aerojet-General (one of the sponsors of the Plastic Housing Research Project of the University of Michigan, 1968, see Ref. 16, pp. 5) has already developed a process for tying the inner and outer skins together at the corners, which involves the insertion of a helical-wound filament coil between the two skins.

c. The winding force:

During the production process of filament wound housing, a problem was discovered which is characteristic of filament winding operations as applied to rectangular sections. Depending on filament's tension, each revolution of the mandrel added approximately 10 kg/cm of force, compressing
the mandrel and threatening it to deform. Furthermore, a certain amount of tension is necessary to insure that the filaments conform to the mandrel surface. In general, rectangular sections require greater tension than do cylindrical surfaces. Thus, slightly curved corners are required when rectangular sections are used.

(Ref. 16, pp. 23-27)
Tools and Equipment:

1. Steel mandrel (includes extended jackscrew). (Fig. 84)
2. Winding tower. (Fig. 85)
3. Elevator carriage. (Fig. 86)
4. Curing area with heat lamps. (Fig. 87)

Critical technical problems:

1. The mandrel has to maintain sufficient filament tension.
2. The mandrel has to be reused.

Implications:

1. High capital investment.
2. High production rate.
3. Excellent quality control.
4. A convex tube-like form is preferred.
5. Sophisticated industrial capacity is needed.
Advantages:
1. Good quality control.
2. High production rate.

Disadvantages:
1. High capital investment.
2. Limitation on the product shape.
3. High-tech environment is needed.
4.1.4 Inflatable Dome

1. Production method:

First, the ground is levelled and a shallow trench about 10cm deep for the foundation is prepared. Then, rods and steel segments for anchorage to stabilize the pneumatic form are assembled. (Fig. 94)

Second, the pneumatic form is fixed on the steel rods and connected with a pump and control system. The form is then inflated. (Fig. 88) Subsequently, fiberglass forms for openings and electric installations are affixed.

Third, a inner layer of foam is applied. Then cables and their connection to the circuits are made. (Fig. 89) Following this, a thermal insulation layer is cast.

Fourth, the outer layer of foam is applied and a sun screen paint to protect the foam may be applied.

Finally, the pneumatic form is deflated and the anchoring segments are unscrewed. The form is then removed from the completed structure. After this, interior finishing is applied in a conventional manner. (Ref. 6, pp. 31)

2. Critical technical points:

a. Deformation caused by loading:

A drastic change in the shape of the pneumatic form is caused by the weight of the foam. For example, if foam is sprayed on the lower part of the form and then the upper part is loaded with the foam, the upper portion of the form will sink, causing a swelling to appear below. This swelling, which increases the diameter of the lower part of
the form, may cause the concrete to crack and collapse.

The size of the swelling will diminish by increasing interior air pressure. But increasing interior air pressure also increases the membrane stress. Thus, the membrane used as the form has to be of high quality and strength to resist this stress.

b. Deformation caused by temperature: (Fig. 90)

The size and shape of the pneumatic form will be affected by normal temperature changes. When the inflated air in the form is stable, there exists a direct proportional relationship between the interior pressure and temperature; that is, with a rise of temperature there is also a rise of the interior pressure, and vice versa.

Deformation caused by temperature changes may be avoided by using a security control valve which increases or decreases the amount of air in the form as required. If the air within the form heats up, thereby increasing the pressure, a enough air is released until the desired pressure is reached; similarly, if, because of leakage or cooling, the pressure drops, more air is pumped into the form to build up the pressure to its required level. Thus pressure can be maintained at a constant level. Air pressure control systems, currently available, are designed for heavy work-load, but their sensitivity is low.

c. Lifting force: (Fig. 91)

The full weight of the interior pressure of the envelope acts at the bottom of the form, creating a lifting force
which tends to uproot the rim of the form from its anchorage to the foundation. This force is much greater than the counter-weight of a conventional foundation and therefore, the foundation may be pulled away from the ground.

This problem can be solved by supporting the form by a system of steel rods, i.e., the bottom of the form rests on a system of rods, arranged radially like the spokes of a bicycle wheel and which are raised above the ground. The forces, therefore, are thus transferred to a circumferential pressure ring which may be of lightly reinforced concrete. (Fig. 94) (Ref. 6, pp. 24-29)
Tools and Equipment:  
1. Spraying gun and air pumps  
2. Pressure control system  
3. Support system for the bottom of the ballon formwork  
(Fig. 93)  
4. Anchoring system (Fig. 92)  

Implications:  
1. Low capital intensive.  
2. Equipment may be expensive since the technology is new.  

Critical Technical Problems:  
1. Deformation of the formwork due to temperature changes.  
2. Lifting force on the form due to the air pressure.  
3. Experienced workers or equipment may be hard to find since the technology is relatively new.  
3. Thickness control.  

Advantages:  
1. No production stage in the factory at all.  
2. Good insulation.
Disadvantages:

1. New technology, high risk of construction failure.
4.2 Erection and Transportation Methods

Method 1: On site erection (inflatable form) (Fig. 94)

Advantages:
1. Cheap formwork.
2. No production time in the factory is needed.
3. No need for transportation.

Disadvantages:
1. Influenced by the Weather.
2. Skilled labour is hard to find.
3. Low erection rate.

Method 2: The system is erected and transported as flat panels (Fig. 95)

1. Transportation and erection of the components can be operated manually.
2. Easy to transport.

Disadvantages:
1. Joints has to be provided on site.
2. If the system is a double curved form, special equipment is needed to bend the panels.

Method 3: The system is erected and transported as curved panel (Fig. 96)

1. The components can be erected and transported manually.

Disadvantages:
1. Hard to transport (not critical).
2. Joints have to be provided on site.

Method 4: The system is erected and transported as a box (Fig. 97)

1. Increasing erection rate.
2. Quality control is better than above.

1. Expensive erection equipments are needed.
2. Hard to transport.
4.3 Subsystems: (Bathroom Units)

Bathroom units used for the plastic house can be divided into the following six groups:

1. Individual components: (Fig. 98)

The tub, shower, toilet, and sink are manufactured as discrete products and attached to built-up walls and floors. Coordinating these activities with each other and with overall building schedule requires very careful coordination.

2. Combined components: (Fig. 99)

The combined-component approach joins elements which are related by function or proximity physically to simplify installation and to achieve visual integration of the space. Typically, these elements include single and double sinks molded in one piece with the countertop, back splash, and water inlet spout, shower and bathtub combinations, as well as vanity and toilet water tank integrated into the vanity.

3. Components with partial enclosures: (Fig. 100)

Partial enclosures are formed by adding factory-produced walls to the tub/shower to create an enclosure that is completely waterproof and has few seal joints. Often, plumbing runs can be surface-mounted and hidden by the GRP walls.

4. Lower half enclosure: (Fig. 101)

Since practically all the wet activities in the bathroom occur below the 1m level, designs that mold sink, toilet, tub, floor, and side walls in one piece are also available.
5. Total enclosure: (Fig. 102)

With the total-enclosure concept, there are two methods of completing a room. In the first, the unit is assembled at the point of manufacture and shipped as a fully packaged box, which is plugged into the basic structure and hooked up from the outside. Construction may then continue around the box. In the second, the unit is molded as a number of large parts, which are moved into the designated bathroom space and assembled on-site. If the parts are sized to fit through standard door widths, they can be installed as required by the building sequence. (Ref. 9, pp. 4-9)
Advantages: | Disadvantages:
---|---

**Individual Components: (Fig. 98)**
1. Style and color variation permitted by volume market. | 1. Multiple on-site joints that may leak and trap dirt.
2. Relative ease of manufacturing. | 2. Need for several trades to complete an installation.
3. Small size for easy shipping and handling. | 3. Susceptibility to handling damage and pilferage.

**Combined Components: (Fig. 99)**
1. Fewer detailed parts for simplified installation and manufacturing. | 1. Requirement for some critical on-site jointing.
2. Fewer on-site joints. | 2. Need for several construction trades.

**Partial Enclosures: (Fig. 100)**
1. Elimination of many on-site joints. | 1. Handling and shipping problems due to large size of pieces.
2. Fewer building trades required. | 2. Susceptibility to damage by remaining trades during construction.
3. Factory finishes used in high-moisture areas. | 3. Need for close dimensional control of rough carpentry.

**Lower-Half Enclosures: (Fig. 101)**
1. Elimination of almost all joints in wet area. | 1. Susceptibility to damage during remaining finishing.
2. Factory finishes in all wet areas other than upper half of shower. | 2. Shipping and handling problems due to large size.
3. Minimized pilferage loss due to large size. | 3. Need for close dimensional control of rough carpentry.
Total enclosures: (Fig. 102)

1. Factory assembling and engineering of all joints.

2. Factory finishes on all surfaces.

3. No on-site trades required to work within the shell.

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<tr>
<td>1. Difficulty in varying standardized design style, color, and materials.</td>
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<td>2. Shipping and handling problems due to large shell sizes.</td>
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<td>3. Higher material unit cost.</td>
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4.4 Joints and Connections

1. Open-drained joints: (Fig. 103)

These joints were developed for use with precast concrete, and work on the basis of a baffle strip located in grooves in the edges of the panel with an airseal located at the back of the panel. They may be used with GRP, subject to a few important factors:

a. Control of form of the panel edge.

b. Control of detailed profiling including rounding of corners:

Profiling of each panel to be jointed must be formed against a mould, rather than around a profiled timber insertion.

2. Preformed strips: (Fig. 104)

The open-drained joints can be simplified into straight preformed strip joints. The most frequent problem with GRP cladding is the tendency for the seal to slide out of the joint in time. This problem is sometimes aggravated by the slight taper on the edge (for demoulding) and by a very glossy surface caused by the residual release agent. Thus, preformed strip joints are generally used only when fixings are made by bolting through the flange.

3. Sealants: (Fig. 105)

Detailing of panel edges is simplest with joints sealed with a gun-applied mastic or sealant but this method requires a high quality sealant and careful joint preparation.

A single seal should not be relied upon as a primary
joint seal where the consequence of sealant failure could result in water penetration into the building. Back-up seals can consist of a second line of sealant, or a preformed strip, with a drained space between.

4. Gasket: (Fig. 106)

When panels are to be sealed together or fittings (window frames etc) are to be fitted into panels, gaskets may be used. The important aspects affecting the production of GRP panels are:

a. The flange on the GRP must be thickened to the same size as the glass/metal fittings on the other side of the gasket.

b. The GRP flange thickness must be more constant than is normally obtained by hand consolidation and the back face must be smoother than the normal finish to obtain a good weather seal. (Ref. 15, pp. 741-745)
Advantages:

Method 1: (Fig. 103)

1. Good water proofing can be achieved.
2. Long term durability.

Method 2: (Fig. 104)

1. Easier to produce than open-drained joints.
2. The seal is tend to slide out of the joint in time. (bolting through flanges is preferred.

Method 3: (Fig. 105)

1. Easy and cheap to erect.
2. Great care is needed to eliminate the tensile or compressive stress on the sealant.
Method 4: (Fig. 106)

1. Easy to assemble and change components.

1. The thickness of the flange of the panel has to be consistent.
4.5 Reinforcement

Single skin construction can be stiffened by a system of ribs on the back of the panel. The depth and position of the ribs determine the overall stiffness obtained.

There are two methods which are generally used for reinforcement:

1. Polyurethane foam and cardboard or paper tubes are commonly used as rib forming means. GRP "top hat" sections can also be pre-moulded and laminated into the panel. (Fig. 107)

2. Timber and metal sections of similar profile to GRP ribs are sometimes laminated into the back of GRP skins to stiffen them, these materials have different coefficients of expansion to GRP and it may be necessary to ensure a mechanical key to GRP rather than rely on adhesion. (Fig. 108) (Ref. 15, PP.621)
Advantages: Disadvantages:

Method 1: Foam or paperboard is used as the reinforcement. (Fig. 107)
1. Low cost.
2. No incompatibility problems between GRP and the reinforcement.
1. Lower stiffness than Method 2.

Method 2: Metal or timber section is used as the reinforcement (Fig. 108)
1. High stiffness can be achieved.
1. Differential thermal movement between GRP and the rib may occur.
   (In general, timber is preferred since it has similar thermal coefficient as GRP.)
CHAPTER 5. DESIGN CONTEXT INTRODUCTION

The design context being chosen for the plastic house design is called Green Bay; a 7500 square meter sea-side site located on the northeast side of Taipei, Taiwan. The site is penetrated by Kin-Ken road, about 40 minutes drive from Taipei during rush hours. (Fig. 109) Green Bay has been planned as a resort development project, which, according to ULI's (the Urban Land Institute) definition (Ref. 20, pp. 4), is a short term destination which provides an assortment of recreational activities, as well as lodging, dining, and entertainment services. Plastic will be used as the major building material for the facilities of this project. The important characteristics which relate to the building system design are identified in the following sections of this chapter.
5.1 Natural Environment

1. Coast length: 2.3km.
2. Topography: 15 degree steep level on the hill-side site, flat on the sea-side site.
3. Area: 7500 square meter.
5. Temperature: 22.3 degree C.
6. Wind: Typhoon is possible.
7. Rainfall: 2102.7mm/ average.

(Ref. 24, pp. 3-5)
5.2 Technical Level

1. No crane or expensive construction equipment is expected to be used.

2. Labour cost is cheaper than machine cost in TAIWAN.

3. Skilled labour for GRP construction is available.
   (transferred from the boat industry.)

4. A factory based on hand lay-up technology is available.
   (no temperature control facility.)

5. Transportation is by pick-up truck with a loading capacity of 0.5 ton to one ton and a cargo bed size of 1.8m by 2m. (5 minutes drive from factory to site.)
5.3 Planning Objectives

   (Ref. 20, pp. 4)

2. 300 plastic house units are needed to be built as second vacation homes.

3. Support facilities: Motel, shop, pavilion, others.

CHAPTER 6. EVALUATION OF ALTERNATIVES

The catalogs for system design which has been established in Chapter 3 and Chapter 4 can be separated into the following:

1. Structural shapes.
2. Production methods
3. Erection and transportation methods
4. Subsystems (bathroom units).
5. Joints and connections.
6. Reinforcement.

Each item presents several alternatives, and one of the alternatives has to be chosen by the designer within that range. Based on the information of the context (chapter 5), an Alpha-Beta table has been built for items 1, 2, 3, to choose the best alternatives (see Ref. 1, pp. 21-25 for the explanation of the Alpha-Beta method). Items 4, 5, and 6 will be only used as a design reference and will not be evaluated by the Alpha-Beta method.
6.1 Structural Shapes:

EXISTING CONDITIONS:

1. The construction of the system should be reasonably cheap.

2. The project is an entertainment center.

3. More than one building type is needed.

4. There are many different family sizes to accommodate.

5. The shelter is the main part to be built by plastic.

DESIGN CRITERIA: (=C)

C-1. Efficient structural shape should be used.

C-2. The form of the system should be as attractive as possible.

C-3. The units of the system can be combined into many variations easily.

C-4. The system should be able to expand and contract easily.

C-5. The system should be easy to combine with other systems.

Alternatives: (=A)


Alpha-Beta Model:

<table>
<thead>
<tr>
<th>Beta-Value</th>
<th>A Value</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>A-5</th>
<th>A-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1 22.5</td>
<td>9</td>
<td>9</td>
<td>8</td>
<td>7</td>
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<td>6</td>
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<tr>
<td>C-2 20</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>9</td>
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<td>C-3 20</td>
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<tr>
<td>C-4 20</td>
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<td>9</td>
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<td>9</td>
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<tr>
<td>C-5 17.5</td>
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<td>7</td>
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<tr>
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</tr>
</tbody>
</table>

According to the table, A-3 has a total score of 8.2 shows it is the best alternative for this project.
6.2 Production Methods:

EXISTING CONDITIONS:

1. The system is used for this project only.
2. The essence of the GREEN BAY PROJECT is a sea side resort, the variation of the building type is very important.
3. A factory which is based on the hand lay-up method exists, workers are transferred from a GRP boat facility to this factory.
4. Labour cost is cheaper than machine cost in TAIWAN.
5. Unstable climate condition.
6. There is no critical pressure on scheduling for the completion date.

DESIGN CRITERIA: (=C)

1. Low capital investment.
2. Production flexibility.
3. Quality control depends on labour's skill.
4. Labour intensive.
5. Reduce the working time on site.
6. Production rate requirement is not critical.

Alternatives: (=A)

A-4. Inflatable Dome

Alpha-Beta Table:

<table>
<thead>
<tr>
<th></th>
<th>A Value</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

Sum 100

According to the table, A-1 has a total score of 9.4 reveals that it is the best alternative for this project.
6.3 Erection and Transportation Methods:

EXISTING CONDITIONS: 

1. No expensive equipment is expected to be used.
2. Labour cost is cheaper than machine cost in TAIWAN.
3. Unstable climate condition.
4. No critical schedule pressure
5. 5 minutes drive to site from the existing factory.

DESIGN CRITERIA: (=C)

1. Labour intensive erection and transportation methods should be used.
2. Reduce erection time on site.
3. Production rate requirement is not critical.
4. Ease of transportation is not critical.

Alternatives: (=A)

1. Total on-site erection  2. Flat panel  3. Curved panel
4. Box

Alpha-Beta Table:

<table>
<thead>
<tr>
<th></th>
<th>A-value</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
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<td>7</td>
<td>9</td>
</tr>
<tr>
<td>C-4</td>
<td>22</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

SUM  100

According to the table, A-3 has the highest score of 8.85 shows that it is the best alternative of this project.
CHAPTER 7. BUILDING SYSTEM DESIGN

According to the outcomes of the evaluation (chapter 6), several critical design principles have emerged as follows:

1. Synclastic shape should be used.
2. Hand lay-up method should be used.
3. The house unit should be erected and transported as curved panels.

Based on these principles, a building should be developed pertaining to the above principles, while at the same time satisfying the requirements of site and use function.
7.1 System Description

7.1.1 Basic Unit (Fig. 110)

The basic unit of the plastic house is a 3.6m wide double curved shelter made up of four identical 1.8m wide panels. The dimension of the basic units and the panels is determined by the following two considerations:

1. Design flexibility:
   3.6m is used as the dimension of the unit width because it allows great flexibility for unit subdivision.

2. Transportability:

   Large panels are preferred for the prefabricated plastic house, since large panels can save construction time, but the size of the panel should be limited to a range that will not cause transportation problems. 1.8m is used as the width of the panels since this size can fulfill both requirements listed above.

7.1.2 Basic Components

1. Panels: (Fig. 111)

   The panels are made by layers of hand lay-up GRP with plywood reinforcement around its edges. The exact width of the panel is 1.775m instead of its nominal width of 1.8m, where 2.5cm is used for the tolerance at the joints. Similar construction is used for the caps. The panel weights 60kg and the cap weights 35kg. Thus, both components can be transported and erected easily by man power. (The unit
weight applied for this calculation is 8kg/square meter for 3mm-4mm thickness GRP laminates.)

2. Other components: (Fig. 112)

Components D, E, F are used to modify the connection points of the panels, where E is used to accommodate the partition system and D is used to accommodate exterior walls and windows. D, E and F are made of extruded PVC which is ordered from the outside manufacturer. The compression ring (component C) made of aluminum is also ordered from an outside manufacturer.

7.1.3 Joints (Fig. 113)

The panels are connected indirectly by providing the components D, E, or F in between. These components provide a place for both tolerance accommodation and electrical distribution. An additional strip of rubber is provided as a further protection for the joints and is also designed to accommodate tolerance and thermal expansion.

7.1.4 Partitions (Fig. 114)

Gypsum dry wall is used as the partition system to be accommodated by either components E or F. Component E is used for the partitions between two basic units and component F is used in the ceiling level for the partition within the basic unit, where E provides an easy subdivision of the space without using special partition components.
7.1.5 Envelope System: (Fig. 115)

The cladding GRP panels are reinforced by plywood and backed up by cardboard to form a flat interior surface. Both the cladding panels and the exterior door and window system are accommodated by components D.

7.1.6 Electrical Distribution: (Fig. 116)

Electrical wiring is put within components E or F which provide a perfect passage for the utility system.

7.1.7 Bathrooms: (Fig. 117, Fig. 118)

Two kinds of prefabricated bathroom are produced for two different house types of unit design; one for the standard type (Fig. 117) and one for a more elaborate design type with built-in furniture. (Fig. 118) The first type is a lower half height enclosure bathroom which is reinforced by plywood around its upper perimeter, where the bathroom is joined to the basic unit. The second one is a partial enclosure bathroom type where the GRP wall is reinforced by plywood strips and backed up by cardboard to achieve a flat surface.

7.1.8 Production and Transportation: (Fig. 119)

The panel is produced in a tilt mold which allows access for the workers to the panel easily, to ensure product quality. Because of the toughness and plasticity characteristics of the material, panels can be stacked
together to make transportation easier in large volume.

7.1.9 Erection Process: (Fig. 120)

First, the site is cleaned and concrete is poured to get a flat surface to place the plastic shelter on. Specially designed steel plates are fastened to the ground for the accommodation of components D and E. A template is put in position for adjustment during panel erection.

Second, panels are jointed to components D and E and the outside strips are provided.

Third, the caps are connected to the basic unit, and the bathroom unit is moved into the house shell and joined with the basic unit.

Finally, finish items are moved into the basic unit, then the cladding panels are provided as a protection and interior finishes are applied by conventional method.

7.1.10 Design Morphologies: (Fig. 121 to 126)

By combining the different catalog items of the basic units, different types of vacation houses or small restaurants can be built by these units. For the Green Bay Project, two basic types of design have been provided in different price ranges for different income groups. Type One is designed to incorporate regular furniture and conventional interior partition arrangements for middle-high income people. Fig. 121 shows the possible plans and furniture arrangements of Type One and Fig. 122 shows the morphological range of Type One. Type Two is designed for
luxury interior arrangements, using specially designed built-in furniture. The target income group is high-income. Fig. 123 and Fig. 124 show the plan types and morphologies of this type, while Fig. 125 is an isometric showing the interior design of the unit.

All the designs listed above are for single family houses. All of these house types can be combined together to form courtyard multi-family housing types which are shown in Fig. 126.

Beyond that, individual panels can be combined to form building types for other functions, such as small restaurants or pavilions. Possible plans for these are shown in Fig. 127.
Fig. 111 BASIC COMPONENTS 1
Fig. 112
COMPONENTS
2
Fig. 113 JOINTS
Example of the exterior panel distribution

Fig. 115
ENVELOPES
Fig. 116
ELECTRICAL DISTRIBUTION
Fig. 117

BATHROOM 1
Fig. 118  BATHROOM 2
tilt mold

mold can be tilted for operation

panels can be packed together for transportation

Fig. 119
PRODUCTION & TRANSPORTATION
Fig. 120
ERECCTION PROCESS
Fig. 121
PLAN TYPES 1
1. BASIC TYPES

2. VARIATIONS

Fig. 122
MORPHOLOGY

3. SUNSHADING TYPES
Fig. 123
PLAN TYPES 2

B2
B4
B1
B3
1. BASIC TYPES

2. VARIATIONS

3. SUNSHADING TYPES

Fig. 124
MORPHOLOGY 2
Fig 125
INTERIOR ISOMETRIC
MULTI-FAMILY TYPES

PAVILIONS

MORPHOLOGY 3
Fig. 126 OTHER POSSIBILITIES
Conclusion:

By using plastic as a building material for house module design, and aside from the advantages of easy forming and easy transportation, the material suggests several other advantages which might be worthwhile to explore in the future, especially from a cost saving viewpoint:

1. Reduction of finishing time:

   Many design features can be incorporated into the structural plastic panel to satisfy many diverse functional requirements. For example, a finished surface can be applied, insulating material added, interior studs can be installed in a single operation during the molding of the panel at a much lower cost than if done separately in the field.

2. Reduction on construction cost:

   Because reinforced plastics are lighter in weight than conventional construction materials, small erection machinery with low lifting capacity requirements can be employed. Also, because of the relatively large size of the panels, the time required to enclose a building is greatly reduced and fewer joints have to be sealed.

3. Energy saving:

   With fuel costs rising and with increasing awareness that the energy problem is a long term phenomenon, plastic contributes to a certain degree to help reduce heating, cooling and illumination. For example, panel wall systems made up of an aluminum grid core (or a polyurethane core)
with translucent fiber glass reinforced plastic panels bonded to both sides can produce a very low U-value. Such composites thus may significantly reduce the heating and cooling load of house modules. (Ref. 14, pp. 123-125)

However, in spite of the many advantages a plastic house can offer, there are also several disadvantages including psychological barriers which have to be overcome before the full potential of this kind of technology can be fully explored. Some of these are:

1. Fire problem:

   In the near future, the most important consideration in building applications is resistance to fire, since building codes and public officials are becoming increasingly concerned not only about fire hazards but also about smoke and gas generated as a by product of combustion of plastics. Fact and myth are mixed in popular conceptions about the fire behaviour of plastics. Even some professionals believe that all burning plastics give off large quantities of toxic gases. This perception needs to be corrected and qualified. However, it is true that many plastics evolve dense black smoke during fire. Whether toxic or not, such smoke easily obscures vision, making escape difficult and inducing panic that can result in disaster. To alleviate this problem, the use of fire-retardant resins and additives in reinforced plastics has shown a marked increase in fire-sensitive applications, and research-intensive programs are being pushed both in the fire retardant and smoke-represent
areas. However, the subject is still highly complex, and far from being satisfactorily resolved.

2. Durability:

Durability under various exposure conditions, existing around and in buildings is another major problem calling for concentrated efforts and practical solutions, if plastics are to experience a major expansion in building. Methods of predicting the long term behaviour of plastics, especially out-doors, the basis of short-time tests are not totally reliable, especially in the absence of long-time experience in actual use. Potential users are understandably reluctant to utilize any new material, including plastics, in the absence of reliable performance.

3. User's psychological resistance:

Finally, probably the most critical problem for a potential plastic house developer, is the user's psychological resistance to the unusual shapes of most plastic houses. Both the modular shell and geodesic designs take advantage of the formability of reinforced plastic to provide efficient shapes that are inherently stiff as well as strong. Most of the house buyers, however, tend to prefer conservative designs, which satisfy their image of "house" as represented by a conventionally built house.

Although nonstructural applications of plastics such as plastic coatings, adhesives, sealants and furnitures, or semistructural application such as cladding panels (which are beyond the range of this thesis) have proven to be a
great success, the drawbacks mentioned above prevent plastic house modules from penetrating the major housing market. However, we must keep in mind that any technology has its own adaptability for certain functions. With its "exotic" shape, foam structure such as Xanadu did penetrate the recreational housing market successfully. With its easy forming and lightness, sandwich construction such as Portable Housing Module was approved for its adaptability for difficult site conditions by the oil exploration industry. Thus, plastic house modules may not adapt to all kinds of functions where a small house shell can be used, but with careful design based on appropriate applications of the properties of plastics, there still is an enormous amount of potential for this kind of structure which is waiting for us to explore.


